The deBroglie-Bohm interpretation

Louis deBroglie (1892-1987)

David Bohm (1917-1992)

"I saw the impossible done..." - John Bell
The deBroglie-Bohm interpretation for many particles

The ontic state: \( \psi(r_1, r_2, \zeta_1, \zeta_2) \)

Wavefunction on configuration space  
Particle positions

The evolution equations:

**Schrödinger’s equation**

\[
\frac{i\hbar}{\partial t} \psi(r_1, r_2, t) = -\frac{\hbar^2}{2m_1} \nabla_1^2 \psi(r_1, r_2, t) - \frac{\hbar^2}{2m_2} \nabla_2^2 \psi(r_1, r_2, t) + V(r_1, r_2) \psi(r_1, r_2, t)
\]

\[
\frac{d\zeta_1(t)}{dt} = \frac{1}{m_1} \left[ \nabla_1 S(r_1, r_2, t) \right]_{r_1 = \zeta_1(t), r_2 = \zeta_2(t)}
\]

\[
\frac{d\zeta_2(t)}{dt} = \frac{1}{m_2} \left[ \nabla_2 S(r_1, r_2, t) \right]_{r_1 = \zeta_1(t), r_2 = \zeta_2(t)}
\]

The guidance equation
\[ \psi = \sum_j c_j \psi_j \]

“waves” of the decomposition

\[ \zeta \in \text{ Spatial support of } \psi_j \quad j\text{th wave is occupied} \]
\[ \zeta \notin \text{ Spatial support of } \psi_j \quad j\text{th wave is empty} \]

If only the \( k\)th wave is occupied

Then the guidance equation depends only on the \( k\)th wave
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i\hbar \frac{\partial \psi(r_1, r_2, t)}{\partial t} = -\frac{\hbar^2}{2m_1} \nabla^2_1 \psi(r_1, r_2, t) - \frac{\hbar^2}{2m_2} \nabla^2_2 \psi(r_1, r_2, t) + V(r_1, r_2) \psi(r_1, r_2, t)
\]

\[
\begin{align*}
\frac{d\xi_1(t)}{dt} &= \frac{1}{m_1} \left[ \nabla_1 S(r_1, r_2, t) \right]_{r_1=\xi_1(t), r_2=\xi_2(t)} \\
\frac{d\xi_2(t)}{dt} &= \frac{1}{m_2} \left[ \nabla_2 S(r_1, r_2, t) \right]_{r_1=\xi_1(t), r_2=\xi_2(t)}
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If only the \( k \)th wave is occupied

Then the guidance equation depends only on the \( k \)th wave
\[ \psi(r_1, r_2, t) = \phi^{(1)}(r_1, t) \chi^{(2)}(r_2, t) \]  

Product state

\[ = R_1(r_1, t)e^{iS_1(r_1, t)/\hbar} R_2(r_2, t)e^{iS_2(r_2, t)/\hbar} \]

\[ S(r_1, r_2, t) = S_1(r_1, t) + S_2(r_2, t) \]

\[ \frac{d\xi_1(t)}{dt} = \frac{1}{m_1} \left[ \nabla_1 S_1(r_1, t) \right]_{r_1=\xi_1(t), r_2=\xi_2(t)} = \frac{1}{m_1} \left[ \nabla_1 S_1(r_1, t) \right]_{r_1=\xi_1(t)} \]

\[ \frac{d\xi_2(t)}{dt} = \frac{1}{m_2} \left[ \nabla_2 S_2(r_2, t) \right]_{r_1=\xi_1(t), r_2=\xi_2(t)} = \frac{1}{m_2} \left[ \nabla_2 S_2(r_2, t) \right]_{r_2=\xi_2(t)} \]

The two particles evolve independently
Reproducing the operational predictions

Consider a measurement of $A$ with eigenvectors $\phi_k(r)$

$$\phi_k(r) \chi(r') \rightarrow \phi_k(r) \chi_k(r')$$
Reproducing the operational predictions

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$$\phi_k(r)\chi(r') \rightarrow \phi_k(r)\chi_k(r')$$

$$[\sum_k c_k \phi_k(r)]\chi(r') \rightarrow \sum_k c_k \phi_k(r)\chi_k(r')$$

Assumption: different outcomes of a measurement correspond to disjoint regions of the configuration space of the apparatus

$$\chi_j(r')\chi_k(r') \simeq 0 \text{ if } j \neq k$$
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Consider a measurement of \( A \) with eigenvectors \( \phi_k(r) \)

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\[
\chi_j(r')\chi_k(r') \approx 0 \text{ if } j \neq k
\]

Probability density of \((\zeta, \zeta')\) being in the support of the \(j\)th wave

\[
|e_j\phi_j(\zeta)\chi_j(\zeta')|^2
\]
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$$\chi_j(r')\chi_k(r') \simeq 0 \text{ if } j \neq k$$

Probability density of $(\zeta, \zeta')$ being in the support of the $j$th wave

$$|c_j \phi_j(\zeta)\chi_j(\zeta')|^2$$

Total probability of the $j$th wave being the occupied wave

$$|c_j|^2$$
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$$\chi_j(r') \chi_k(r') \sim 0 \text{ if } j \neq k$$

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If the $j$th wave comes to be occupied, then one can postulate an effective collapse of the guiding wave

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Effect of decoherence

Consider a measurement of $A$ with eigenvectors $\phi_k(r)$

$$\phi_k(r)\chi(r')\eta(r'', r''', \ldots) \rightarrow \phi_k(r)\chi_k(r')\eta_k(r'', r''', \ldots)$$
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Distinct states of environment correspond to disjoint regions of the configuration space

$$\eta_j(r'', r''', \ldots)\eta_k(r'', r''', \ldots) \approx 0 \text{ if } j \neq k$$
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To have re-interference with the empty waves, it would be necessary to map all the $\eta_k$ back to $\eta$
Do measurements reveal attributes of the particles?

Position measurements are “statistically faithful”:

$$\langle \psi | F(\mathbf{R}) | \psi \rangle = \int d\zeta \ F(\zeta) \ \rho(\zeta)$$
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But momentum measurements are not:

although

$$\langle \psi | P | \psi \rangle = \int d\zeta \ \left( m \ \frac{d\zeta}{dt} \right) \ \rho(\zeta)$$

we have, for example:

$$\langle \psi | \frac{P^2}{2m} | \psi \rangle \neq \int d\zeta \ \left( \frac{1}{2} m \ \left( \frac{d\zeta}{dt} \right)^2 \right) \ \rho(\zeta)$$
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If we define energy as a function of the configuration and the wavefunction

\[ \varepsilon_\psi(\xi) = - \frac{\partial S(r,t)}{\partial t} \bigg|_{r=\xi(t)} = \left[ \frac{(\nabla S)^2}{2m} + Q(r) + V(r,t) \right] \bigg|_{r=\xi(t)} \]

Recall imaginary part of S.E. is

\[ \frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + Q + V = 0 \]
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then it is not conserved in detail, but is conserved on average

\[ \int d\zeta \rho(\zeta, t) \varepsilon_\psi(\zeta) = \int dr \left| \psi(r, t) \right|^2 \left[ \frac{(\nabla S)^2}{2m} + Q + V \right](r, t) \]
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\[ \int d\xi \rho(\xi,t)\varepsilon_{\psi}(\xi) = \int dr |\psi(r,t)|^2 \left[ \frac{(\nabla S)^2}{2m} + Q + V \right](r,t) \]

\[ = \int dr \psi^*(r,t) \left[ -\frac{\hbar^2}{2m} \nabla^2 + V(r) \right] \psi(r,t) \]
Contextuality

No overlap in 3D

Overlap
Contextuality
Contextuality

“Surrealistic“ trajectories?
Contextuality

“Surrealistic” trajectories?

Conclusion: it does not make sense to associate an attribute with an operator without also specifying the full experimental arrangement.
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"Surrealistic" trajectories?

Conclusion: it does not make sense to associate an attribute with an operator without also specifying the full experimental arrangement.

Note however that a criticism remains: deBroglie-Bohm has
Classical limit

Operational correspondence vs. Ontological correspondence
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Do we need to recover Newtonian trajectories for macroscopic objects?
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Operational correspondence vs. Ontological correspondence

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If so, there are problems
One example: Newtonian trajectories can cross
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Possible solution: Decoherence in configuration space
Eliminates interference, thereby allowing crossing
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Failure of Lorentz invariance

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There are deBroglie-Bohm interpretations of relativistic quantum field theories, but these too fail to be Lorentz-invariant.

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Response:
Lorentz invariance is an emergent symmetry - a statistical consequence of quantum equilibrium.
The underdetermination criticism

Underdetermination: when there are many possible choices of ontological structure that are consistent with observations.
Underdetermination of the supplementary variables

Standard approach - Position preferred
Underdetermination of the supplementary variables

Standard approach - Position preferred

The ontic state: \((\psi(r), \zeta)\)

Wavefunction in position rep'n

Particle position

\[ i\hbar \frac{\partial \psi(r,t)}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi(r,t) + V(r)\psi(r,t) \]  
Schrödinger's eq'n

\[ \frac{d\zeta(t)}{dt} = \frac{1}{m} \left[ \nabla S(r,t) \right]_{r=\zeta(t)} \]  
The guidance eq'n

where \( \psi(r,t) = R(r,t)e^{iS(r,t)/\hbar} \)
Underdetermination of the supplementary variables

Alternative approach - Momentum preferred (Epstein, 1952)
Underdetermination of the supplementary variables

Alternative approach - Momentum preferred (Epstein, 1952)

The onctic state: \((\psi(p), \pi)\)

Wavefunction in momentum rep'n

Particle momentum

The evolution equations:

\[
\frac{i\hbar}{\partial t} \psi(p,t) = -\frac{p^2}{2m} \psi(p,t) + V(i\hbar \nabla_p) \psi(p,t)
\]

Schrödinger's eq'n

\[
\frac{d\pi(t)}{dt} = \frac{1}{m} \left[ \nabla_p S(p,t) \right]_{p=\pi(t)}
\]

The guidance eq'n

where \(\psi(p,t) = R(p,t)e^{iS(p,t)/\hbar}\)
Underdetermination of the supplementary variables

This freedom is based on the canonical transformation:

\[ r' = p \]
\[ p' = -r \]
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Response:

-- There are mathematical difficulties with potentials such as

\[ V(r) = e^2 / |r| \]
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The problem returns for the case of a deBroglie-Bohm theory of the electromagnetic field:

Supplementary variable: Electric field or Magnetic field?
Underdetermination of the supplementary variables

Multiple treatments of spin:
Underdetermination of the supplementary variables

Multiple treatments of spin:

Bohm, Schiller and Tiomno approach
Supplementary variables: particle position and orientation

The particle is taken to be an extended rigid object which makes a ‘spin’ contribution to the total angular momentum
Underdetermination of the supplementary variables

Multiple treatments of spin:

Bohm, Schiller and Tiomno approach
Supplementary variables: particle position and orientation

The particle is taken to be an extended rigid object which makes a ‘spin’ contribution to the total angular momentum

or

Bell’s minimalist approach
Supplementary variables: particle position

The effect of spin is seen only in the dynamics of the particle positions
The operational predictions are reproduced by virtue of localization of pointers
Bell’s minimalist approach to spin
Bell’s minimalist approach to spin

The ontic state: \((\psi(r), \zeta)\)

Two-component wavefunction

Particle position

\(\psi(r, t)\)

\(\zeta(t)\)
Bell’s minimalist approach to spin

The ontic state: \( (\psi(r), \zeta) \)

\( \Rightarrow \) Two-component wavefunction \( \Rightarrow \) Particle position

\[ i\hbar \frac{\partial \psi(r,t)}{\partial t} = \left[ -\frac{\hbar^2}{2m} \left( \nabla - \frac{ie}{\hbar c} A \right)^2 + \sigma \cdot B + V(r) \right] \psi(r,t) \]

Pauli eq’n
Bell’s minimalist approach to spin

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Two-component wavefunction

Particle position

\[
i\hbar \frac{\partial \psi(r,t)}{\partial t} = \left[ -\frac{\hbar^2}{2m} \left( \nabla - \frac{ie}{\hbar c} A \right)^2 + \sigma \cdot B + V(r) \right] \psi(r,t) \quad \text{Pauli eq'n}
\]

\[
\frac{d\zeta(t)}{dt} = \left. \frac{j(r,t)}{R(r,t)} \right|_{r=\zeta(t)} \quad \text{The guidance eq'n}
\]

where \( R(r,t) = \sum_s |\psi_s(r,t)|^2 \)

\[
j(r,t) = \sum_s \left( \frac{\hbar}{2m} (\psi_s^* \nabla \psi_s - \psi_s \nabla \psi_s^*) - \frac{e}{\hbar} A \psi_s \psi_s^* \right)(r,t)
\]
Underdetermination of the supplementary variables

Multiple treatments of quantum electrodynamics:
Underdetermination of the supplementary variables

Multiple treatments of quantum electrodynamics:

Bohm’s model of the free electromagnetic field
Supplementary variables: electric field (or magnetic field)

combined with

Bell’s model of fermions (indeterministic, discrete) or Colin’s continuum version of it
Supplementary variables: fermion number at each lattice point
(Note: field variables for fermions have been problematic)
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Bohm’s model of the free electromagnetic field
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Supplementary variables: fermion number at each lattice point
(Note: field variables for fermions have been problematic)

or

Struyve and Westman’s minimalist model of QED:
Supplementary variables: magnetic field (or electric field)
(the classical EM field carries an image of pointer positions)